Improving design for recycling - Application to composites

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IMPROVING DESIGN FOR RECYCLING - APPLICATION TO COMPOSITES

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Abstract: The use of composite material increases. End of life regulations, material consumption reductions or restrictions, ask engineers about their potential use. Innovative recycling solutions arise that recover efficiently carbon fibres. This paper explores the design for composites recycling issue. Recycler becomes a new knowledge expert for the designer. It is necessary to analyze their information shares and exchanges. The recycler is an end of life facilitator. He is also the second life material user and can ask for material evolutions. The collaboration must be improved using knowledge performance indicators. These discussions will be enlightened by examples from carbon recycling experiments.
Keywords: Design method, Recycling, Composite

1. Introduction to composite design and recycling interaction

Today sustainable development becomes a necessity for design and manufacturing. Less material-energy consumption for a controlled and reduced pollution are the key objectives. Composites provide good opportunities, combining high modulus materials with free definition of geometry. Carbon fiber reinforced composites (CFRCs) [1] and more especially thermoset matrix based composites are currently used by the aerospace, aeronautics and automotive industries. They also become used in leisure and sports field. High-tech industries have high quality requirements for the materials, but few integrate end of life aspects. On the contrary, industries for large public application start taking into account this perspective and include the recycled materials in their products. Regulations (focusing on the recycling rate to be achieved by products) are increasing this dynamic. It becomes necessary to take into account the end-of-life (EoL) of carbon fibre/thermoset composites by (i) avoiding landfill or energy recovery (i.e. incineration), and (ii) exploring the carbon fibre recovery via new stakeholders in transport, leisure and sports fields.

Composite design is driven by mechanical characteristics improvements, searching for lighting mechanical structure, and ensuring a mastered behaviour during the product life stages. The design phase integrates complexes decisions algorithm. The product optimisation (shape, mass and costs) depends on the material characteristics (glass, carbon, aramide, natural, etc ...), the type of reinforcement (uni directional or multi directional plies, 2D or 3D orientations, woven or non crimp fibbers). The reinforcement can be made of mix of different fibbers nature depending on the objective mechanical properties, density and costs. Manufacturing processes (TRM, filament winding, pultrusion, contact moulding, etc.) limit the use of some kinds of reinforcements [2]. These processes are mostly chosen due to their geometry possibilities and the final use of the product. Aerospace and aircraft application have strong requirements that limit and reduce the possible manufacturing process (either for fibbers placement and matrix curing) [3]. In addition, some reinforcements don't fit to some geometry such as corners, angle shapes or spherical areas. The fibres orientation (woven) slide and the expected reinforcements are lost. Many constrains interact in the composite part design process. They go one step further with the need of part assembly. Gluing gives efficient solutions, but many applications demand rivets or bolts (metallic) connection for security. It results hybrid assemblies and non perfectly mastered behaviour of the structures. Thus, the optimisations gains are limited. To solve this multi entrance decision systems, designer often impose the manufacturing process or the material and reinforcements. The design optimisations consist in minimising thickness, id es the number of plies with respect of the symmetrical orientation requirements to balance internal residual stress and distortions. This optimisation should succeed to all the loading cases of the product or assembly. No evident composite design methodology arises and gives a real alternative to product/material/process multi choices selection [4]. However, the comparative criteria already exists (specific resistance, delamination criteria and cycling limits, total mass and costs) and new one arises like manufacturing time that becomes a key issue for large audience applications such automotive.

In this perspective taking recycling consideration into account during the design phase can be done with proposal of simple guidelines in order to ease i) dismantling (for example: mechanical assembly should be preferred to a mix of mechanic and glue), ii) matrix-fibres separation (for example: no metallic inserts or limits the massive area thickness), iii) material recognition before and after recycling (for example: use one single type of fibres in a structure). But today, these considerations are far from designer's interests. The only way to make them taking recycling aspects into consideration is to provide cheap recycled reinforcement fibres with good mechanical properties. We first developed a remanufacturing process of recycled carbone fibres [5]. We have to give the materials and mechanical information to the designers in the perspective of the design product use and to inform them on the real recycled fibre history.

In this paper, we will first focus on the recycling of CFRCs, with a particular attention to the current limitations and legislations in force and those to come. We will see that up today, the recycling of CFRCs especially concerns the fibre itself. In the second part, we will study the possibilities of recovery and the improvement expected for the recycling of CFRCs.

2. The recycling of CFRCS

2.1 Legislation in force for composites

Composites are not differentiated within legislation. Their EoL is indirectly involved in the waste electrical and electronic equipment directive (WEEE) [2] and in the legislation for landfill of wastes [6]. Composites are also mentioned in the Reach legislation (Registration, evaluation, authorization and restriction of chemicals) as soon as they contain some toxic or harmful substances such as flame-retardants, currently used in aeronautics. Only the legislations on end-of-life vehicles (ELVs) mention composites recycling. Indeed, the rate of reuse and recovery should reach 95% in 2015, and 85% for reuse and recycling, in average weight per vehicle and per year, according to the European directive "VHU 2000/53" [7].

European directives about WEEE and end-of-life thus force industries to seek new methods of recovery for composite parts. In this context, composites recycling will increase in terms of quantity due to the creation of dismantling platforms. As local examples, in southwest of France, the TARMAC Aerosave[1] platform is dedicated to civil aircraft applications in collaboration with EADS-Airbus and EADS-Sogerma. They mainly focus on reuse and certification of replacement parts in aircraft maintenance. Also, the P2P platform (clean platform for dismantling and testing of solid propellant from defense and embedded systems products) deals with the disassembly of ballistic weapons.

2.2 Assessment of CFRC recycling

Landfill and energetic valorisation are the oldest options for composites EoL. Knowing that CFRCs are made with non-renewable materials and that they are quite expensive (e.g. carbon pre-preg: approx. 180 €/kg), giving them a new life by recycling is a better option both economically and environmentally. Recycling a composite means: i) having a recycling technology available, ii) getting a dismantle solution and an access for the product, and iii) disposing identification plus selection possibilities to the materials. Thus, carbon fibres recovery would both help design engineers to balance energy efficiency and cost, and open new opportunities for developing second-life composites, dedicated to the manufacture of medium or low loaded parts (non-structural in many cases).

Several techniques exist in order to recycle CFRCs [8]. The mechanical recycling consists in grinding fibre and matrix. It's cheap but very aggressive and destructive for the carbon fibres [9][5]. The ground material is reincorporated as filler (powder) or used in a chopped strand mat (short fibres). A last option consists in their use as a mineral phase in concrete. The mechanical recycling is merely in a material valorisation. The thermal recycling can be led by oxidation in fluidized bed, by pyrolysis, or by treatment in molten salt bath [10]. Pyrolysis is the technique that is the more used at the present time. The oxy-thermal effect on the carbon fibre reduces its initial mechanical properties. The chemical recycling (based on the matrix solvolysis by fluid under supercritical conditions) includes all methods of cold recycling (temperature lower than 450°C, and pressure around 250 bar, depending on the matrix polymerization degree), with the use of chemicals [10].

Pimenta presents a synthesis of each technique advantages and drawbacks. But the main limitation for the use of recycled CFRCs (rCFRCs) remains in the fibre length. Consequently they are mainly used for as ground material forms in the cements for civil engineering or integrated in non-structural parts (e.g. as filler) in the automotive industry.

Pyrolysis or Solvolysis methods give the opportunity to recover quite long carbon fibres and to preserve mechanical properties. The fibre length thus directly depends on both size of the to-recycle piece (pre-preg off-cut or end of life part) and dimension of the chemical reactor. The resulting recyclate retains up to 90 percent of the fibre's mechanical properties. In some cases, the method enhances the electrical properties of the carbon recyclate because the latter can deliver a performance close or superior to the initial material [11]. Nevertheless, the economic viability of the chemical recycling solution including chemical processes has yet to be demonstrated and validated on an industrial scale.

In such cases, second use of composite fibres will be dedicated to the manufacture of medium or low-loaded parts (non-structural in many cases). Their use will also depend on the consolidation possibility: alignment ratio, woven possibility, thickness performance, and use in the existing composite process. Pimenta presents an overview of the possible application depending on the recycling process (then the mechanical properties) and the composite manufacturing process. Foreseen markets exist: automotive (in semi-structural parts) and leisure and sports industries [10].

For all these reasons, it is necessary to improve the carbon fibres recycling processes and to integrate these possibilities in the composite product design phase. Cheaper materials with good properties could find larger applications than composites today and with a more environmental-friendly impact.

3. DESIGN FOR "X" APPROACHES

The Design for "X" (DFX) refers to integrated design approaches or the concurrent engineering as proposed by Sohlenius [12]. It points out issues that occur in the different phases of the product life cycle. This integration is supported by design guidelines or design rules. From a knowledge-based point of view, these elements represent an explicit form of knowledge that contains information about "knowing-how-to". This knowledge to formalize and integrate is related to elements issues that are caused (or affected) by the characteristics of a product. The Design for "X" proposes methods and engineering environments that help to generate and apply technical knowledge in order to control, improve, or even invent particular characteristics of a product**.** This approach proposes for each phase of the real product life cycle some knowledge integration as formalized by Pahl who gives a classification of the design for "X" relatively to the product phase. [13]. Shu proposed the Axiomatic Design in order to structure and understand design problems and the links between the different expertises [14].

The development phase leads to design rules for innovation [15] mass customization [16][17] or design for standards. Eco-design concerns feed the Design for Environment approaches [18][19]. The production phase points out design for manufacturing and manufacturability [20] with many specific proposals for each process. Lenau highlights the needs for exchanges between material science experts and designers in order to reconsider the material choice method in parallel with manufacturing process, initiation of the product-process-material method [21]. The design for assembly had many studies promoted by the automation and the subdivision of products in functional modules [22] and also starts integrating disassembly questions [23]. The use phase integrates user focuses (ergonomic or aesthetics) or after sales focuses (maintainability or serviceability). Finally the end of life phase promotes the design for disassembly [24] for further valorisation such as reuse, remanufacturing [25] or recycling [26]. The separation plays a major role in the recycling efficiency [27][28].

The design to cost has a specific position because the cost is affected by all the phases of the product. Through engineering design: i) physical interfaces between parts or components or assemblies of the product and, ii) the manufacturing equipment as well as the logistical material flow systems can be changed, and thus cost reducing effects in operating the latter may be achieved [29].

This brief overview confirms that environments interests arise in all the phases of the product life cycle concerns and start being studied specifically or in addition with an already existing approach. However, the recycling (or end of life solution for products) is little addressed as a specific research. Nevertheless, Ardente developed the ENDLESS software in order to compare end of life alternatives [30][31]. Our proposal is deeper in connection with the recycling processes. We integrate information at the material and process level. The information help designer decisions related to: i) the future use of recycled materials and, ii) the anticipation of end of life product. We build a generation material follower that will be the starting architecture of the supporting environment tool for decision helper. The key point is to identify (before integration) the

[1] http://www.tarmacaerosave.aero/

exchanged information between recycler designers and material science experts.

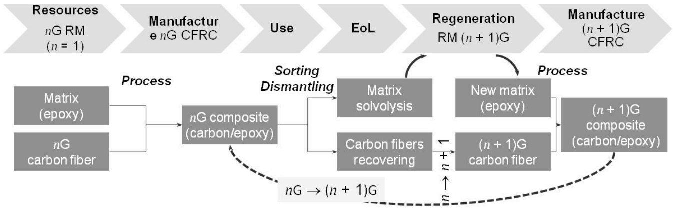

Figure 1. Lifecycle of a CFRC, from resources to the carbon fibre regeneration

4. COMPOSITE RECYCLING

We developed a recycling process based on the solvolysis technology (supercritical fluid) to separate thermoset matrix and the carbon fibres. Thanks to this, the lifecycle of the carbon fibres (CF) is extended by the CF regeneration that allows the cycle to be closed as illustrated in **Erreur ! Source du renvoi introuvable.**. We propose to follow "generation" evolution (1rst generation 1G, 2nd generation 2G, etc) of the fibres in order to predict its future integration in a product design due to the little loss of mechanical properties after recycling. It is also necessary to master the use of the nG-CF (n Generation of Carbon Fibre) in order to fit the mechanical needs and the material possibilities. Thus, the composite based on this reinforcement will be called nG composite. In reality today, product lifecycles from different industries are not connected and the carbon reinforcement is at best promise to an energetic valorisation (dotted line on Figure 2). Considering the aeronautics, automotive and leisure and sports industries, products lifecycles work in closed system (i.e. there are no interactions between them), but not necessarily in closed lifecycle (maybe except for the automotive industry that allows the use of ground composites).

We propose to link these three industries by improving CFRCs' end-of-life. As soon as an industry does accept rCFRCs from another one, they are linked together. Specialists of the EoL have opportunities to improve a material usually non upgradable in a new potential source of raw material. Taking into account the limitations previously listed (length of the recovered fibre, designers' reluctances, etc.), the complete CF lifecycle can be drawn as in **Erreur ! Source du renvoi introuvable.** diagram. It is a cylindrical representation of the successive integrations of the (recycled) CF in different product lifecycles. Only the main steps of each lifecycle are displayed: i) integration of the raw materials (in particular carbon reinforcement); ii) design, process and production of the composite; iii) logistic, product distribution and transport; iv) use and maintenance; v) product end-of-life.

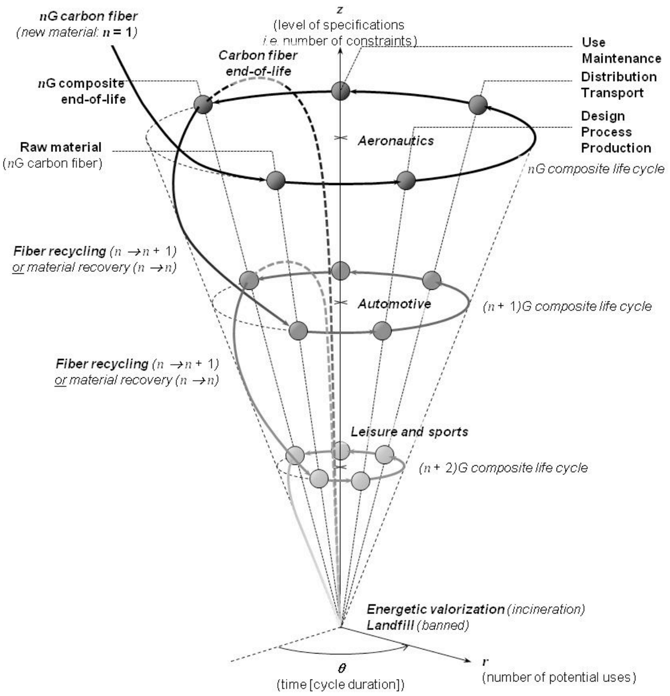

Figure 2. Multi-circular representation of the CF lifecycle. Integration of the (r)CF in successive product lifecycles, depending on their level of specifications (i.e. number of constraints). The radius r of each lifecycle depends on the number of potential uses for the (r)CF.

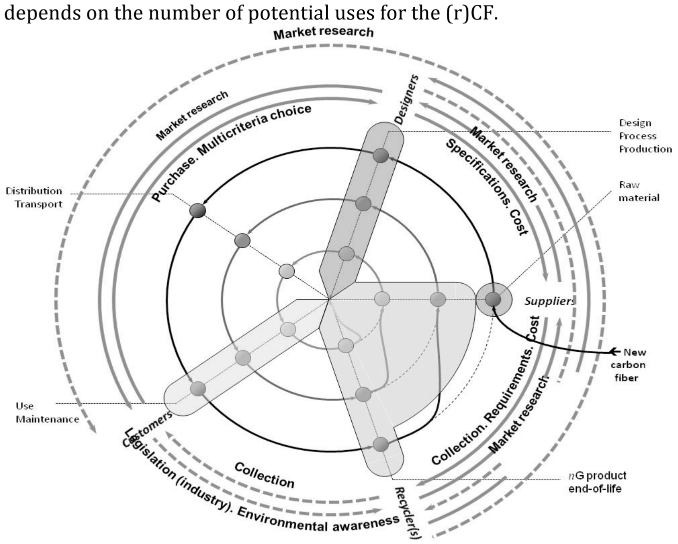

Figure 3: Figure 2 seen from above - stakeholders (grey area: suppliers, designers, customers and recyclers) and their interactions.

Based on this lifecycle and on our expertise, each recycling step can be detailed and a recycling line for carbon fibre can been designed. The *n*G product is first sorted. Indeed, specific coatings like metallic cladding for electric behaviour are not compatible with some recycling processes. Then the product is dismantled (all metallic insert have to be extracted) and cut (*i.e.* adapted to the recycling process reactor). After the solvolysis process, the carbon fabric is recovered as flat plies. The remanufacturing starts with the reprocessing of these fibres in order to make them new possible reinforcements. The fibres are hackled, possibly mixed (depending on available CFs, or on the quality of the chosen reinforcement for the (n + 1)G material), and reinforced to be integrated more easily in the next recycling stage (*e.g.* pre-preg). Depending on the (n + 1)G composite elaboration process (RTM, infusion, etc.), fibres can be spun, then rewoven or knit, or made available as pre-preg strips, to finally process the composite.

5. Actors interactions identification

The Figure 3 corresponds to the **Erreur ! Source du renvoi introuvable.** seen from above. The lifecycles of each of the three industries are linked by exchanges of carbon fibres at the end-of-life stage. The stakeholders and their interactions are identified as follow: i) Suppliers adapt their offer from the designer's needs (market research). They should also be related to recyclers who have to take into account the specifications and cost of the raw materials. ii) Designers are getting information from customers with market research; they choose suppliers according to raw materials specifications and cost. iii) Customers decide to buy or not the product, according to multi-criteria decisions; they are related to recyclers by legislation (for industrials) or thanks to environmental awareness (for individuals). iv) Recyclers are those collecting used CFRCs, whose deposit must be taken into account, as it is becoming stable in terms of source of supply. They then become the new suppliers in the carbon fibre lifecycle, by revalorizing wastes with alternatives to burning. They choose the appropriate recycling process in order to propose a material adapted to the (n+1) designer's needs.

We promote discussion between designers and recyclers in order to innovate in the definition of new recycled composite products (as presented in Figure 4). This means that information and skills from both sectors will be shared. However, it also implies that materials and mechanical knowledge have to be developed for both designers and recyclers. Therefore, it is necessary to include a third party in the discussion: experts in material and mechanical characterization. Moreover, in the carbon fibre recycling line, discussions between stakeholders must be improved by defining semi-products specifications and formalizing those interactions by quality criteria. The latter are based on the processes efficiency.

Figure 4. Natec pedal crank made with rCFRCs (desired characteristics: specific stiffness and equivalent mass to the classic one 185 g)

6. Conclusions and perspectives

CFRCs recycling is a quite recent problematic, due to the increase in their use. As a consequence, the legislations in force barely cite composite materials; they are simply mentioned in the WEEE and ELVs directives. As a consequence, both industrialists and individuals have yet to become aware of the usefulness of CFRCs recycling. However, a recycling network, capable of processing the CFRC recycling (and not only an energetic valorisation) tends to develop.

We have spotlighted that the improvement of local or regional sorting and dismantling platforms remains necessary. Based on the solvolysis process, the recycling is thus achievable. But a sorting and collection network must be developed to feed the recycling line at an industrial scale. All the stakeholders to involve in this line already exist; we now aim to link them. Promoting discussion between designers and recyclers in order to innovate in the definition of new recycled composite products will induce the creation of exchange platforms, allowing information from both sectors to be shared. However, it also implies that materials and mechanical knowledge have to be developed for both designers and recyclers. Therefore, it is necessary to include a third party in the discussion: experts in material and mechanical characterization. Lastly, promoting carbon fibre end-of-life would reinforce the link between aeronautics, automotive, and leisure and sports industries; but one can create demand for recycled reinforcement, by packaging it in useful and attractive forms for those end-users. Lastly, the leisure and sports industries seem to already propose the most important niche markets that could make the use of rCFRCs to come into effect.

References

[1] Piñero-Hernanz, R., Garcia-Serna, C., Chemical recycling of carbon fibre reinforced composites in nearcritical and supercritical water. Composites Part A: Applied Science and Manufacturing, Vol. 39 (3), pp. 454-461. 2008.

[2] Barbero, E.J., Introduction to Composite Materials Design, CRC Press, 562p., 2010.

[3] Jaunky, N., Knight. N.F., Optimal design of grid-stiffened composite panels using global and local buckling analyses, Journal of aircraft, vol. 35-3, pp. 478-486, 1998.

[4] Gay, D., Hoa, V., Composite materials: design and applications, CRC Press, 562p., 2007.

[5] Mantaux, O., Aymonier, C., Antal, M., Recycling of carbon fibre reinforced composite materials with super- critical water dissolution. JNC16 Proc., 2009.

[6] European Parliament. Directive 2008/34/EC of the European Parliament and of the Council of 11 March 2008. L 81/65, 20.3.2088. 2008.

[7] European Parliament. Directive 2006/121/EC of the European Parliament and of the Council of 18 December 2006, L 396, 30.12.2006) : s.n., 2006.

[8] Liu, Y., Recycling of Carbon/Epoxy Composites. Journal of Applied Polymer Science, Vol. 94/5, pp. 1912-1916. 2004.

[9]. Mantaux, O., Chibalon, L., Lorriot, Th., Aurrekoetxea, J., Puerto, A., Arostegi, A., Urrutibeascoa, I, Recycling study of end of life products made of ABS resin, Journal of Materials and Science & Technology, Vol. 20, Suppl.1. 2004.

[10] Pimenta, S., Pinho, ST., Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook. Waste Management, Vol. 31 (2), pp. 378-392. 2011.

[11] Perry, N., Kromm F.X., Mantaux O., Pilato A., Composite eco-design. IFIP AMPS 2010 Conference, Como, Italia. 2010.

[12] Sohlenius, G., Concurrent Engineering, CIRP Annals – Manufacturing Technology, Vol. 41/2, P.645, 1992

[13] Pahl, G., Beitz, W., Engineering Design - A Systematic Approach, Springer, 545p., 2003

[14] Suh, N.P., The Principles of Design, Oxford University Press, 1990

[15] Meier, H., Massberg, W., Life Cycle-Based Service Design for Innovative Business Models, CIRP Annals – Manufacturing Technology, Vol. 53/1, P.393, 2004

[16] Tseng M.M., Jiao, R.J., Wang, C., Design for Mass Personalization, CIRP Annals – Manufacturing Technology, Vol. 59/1, P.1752010

[17] Daaboul, J., Da Cunha, C., Bernard, A., Laroche, F., Design for Mass Customization: Product variety vs. Process variety, CIRP Annals – Manufacturing Technology, Vol. 60/1, P.169, 2011

[18] Wallace, D.R., Suh N.P., Information-based design for environmental problem solving, CIRP Annals – Manufacturing Technology, Vol. 42/1, P.175, 1993

[19] Hauschild, M.Z., Jeswiet, J., Alting, L., Design for Environment approaches? Do We Get the Focus Right? CIRP Annals – Manufacturing Technology, Vol. 53/1, P.1, 2004

[20] Bralla, J., Design for Manufacturability Handbook 2nd ed°, McGraw-Hill ed°, ISBN-13: 978-0070071391, 1998

[21] Lenau, T., Alting, L., The missing element in design for manufacture, CIRP Annals – Manufacturing Technology, Vol. 45/1, P.105, 1996

[22] Boër, C.R., Pedrazzoli, P., Sacco, M., Rinaldi, R., Integrated Computer Aided Design for Assembly Systems, CIRP Annals – Manufacturing Technology, Vol. 50/1, P.17, 2001

[23] Boothroyd, G., Alting., L., Design for Assembly and Disassembly, CIRP Annals – Manufacturing Technology, Vol. 41/2, P.625, 1992

[24] Harjula, T., Rapoza, B., Knight, W.A., Boothroyd, G., Design for disassembly and the environment, CIRP Annals – Manufacturing Technology, Vol 45/1, P.109, 1996

[25] Sherwood, M., Shu, L.H., Fenton, R.G., Waste-stream analysis of independent and original equipment automotive remanufacturers to support design for remanufacture, CIRP Annals – Manufacturing Technology, Vol. 49/1, P.87, 2000

[26] Sodhi, M., Knight., W.A., Product design for disassembly and bulk recycling, CIRP Annals – Manufacturing Technology, Vol. 47/1, P.115, 1998

[27] Knight, W.A., Sodhi, M., Design for bulk recycling: analysis of materials separation, CIRP Annals – Manufacturing Technology, Vol 49/1, P.83, 2000

[28] Lange, S., Schmidt, H., Seliger, G.,Product and assembly design for a fibre reinforced plastic track wheel, CIRP Annals – Manufacturing Technology, Vol. 49/1, P.105, 2000

[29] Mauchand, M., Siadat, A., Bernard, A., Perry, N., Proposal for Tool-based Method of product Cost Estimation during Conceptual Design, Journal of Engineering Design, Vol 9/2, pp. 159-172, 2008

[30] Bernard, A., Perry, N., Delplace, JC., Concurrent Cost Engineering for decisional and operational process enhancement in a foundry, International Journal of Production Economics, Vol. 109/1-2, pp2-11, 2007

[31] Ardente, F., Beccali, G., Cellura., M., Eco-sustainable energy and environmental strategies in design for recycling: the software "ENDLESS", Ecological Modelling Vol. 163, p. 101–118, 2003